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Omnidirectional piezo-optical ring sensor for enhanced guided wave structural health monitoring

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Abstract

This paper presents a novel method for the detection of ultrasonic waves from acoustic emission events using piezoelectric wafer active sensors (PWAS) and optical fiber Bragg grating (FBG) sensing combined with mechanical resonance amplification principles. The method is best suited for detecting the out-of-plane motion of the AE wave with preference for a certain frequency that can be adjusted by design. Several issues are discussed: (a) study the mode shapes of the sensors under different resonance frequencies in order to understand the behavior of the ring in a frequency band of interest; (b) comparison of analytical results and mode shapes with FEM predictions; (c) choice of the final piezo-optical ring sensor shape; (d) testing of the piezo-optical ring sensor prototype; (e) discussion of the ring-sensor test results in comparison with conventional results from PWAS and FBG sensors mounted directly on the test structure. The paper ends with summary, conclusions, and suggestions for further work.

Keywords: piezo, optical, ring sensor, piezoelectric wafer active sensor, PWAS, structural health monitoring

(Some figures may appear in colour only in the online journal)

1. Introduction

Structural health monitoring (SHM) is an area of growing interest and worthy of new and innovative approaches. The increasing age of our existing infrastructure makes the cost of maintenance and repairs a growing concern. SHM may alleviate this by replacing scheduled maintenance with as-needed maintenance, thus saving the cost of unnecessary maintenance, on one hand, and preventing unscheduled maintenance, on the other hand. For new structures, the inclusion of SHM sensors and systems from the design stage is likely to greatly reduce the life-cycle cost.

1.1. SHM methods

SHM can be performed in two main ways: (a) passive SHM, and (b) active SHM. On one hand, passive SHM just ‘listens’ to the structure. In the conventional approach, passive SHM measures various operational parameters (flight parameters, vibration levels, acceleration, strain, pressure, temperature, etc) and processes them to infer the state of the structure. More recent developments in passive SHM include impact detection and acoustic emission (AE) [1]. On the other hand, active SHM ‘pings’ the structure with ultrasonic waves and records the structural response using an array of sensors; in this respect, active SHM resembles ultrasonic nondestructive evaluation (NDE) with the proviso that the transducers (transmitters and receivers) are permanently installed into the structure. For these reasons, active SHM can be also viewed as ‘embedded NDE’ [2]. In both cases, a network of permanently attached sensors capture the elastic waves produced by the impact or AE events and, through processing, determine the event location and amplitude.

Guided-wave active SHM has been shown able to detect cracks and corrosion in metallic structures and debonds and delaminations in composites [3, 4]. Guided-wave active SHM uses pitch-catch, pulse-echo, phased-array and other wave-propagation techniques to detect the signal changes generated...
by the presence of structural damage. These signal changes could be in the form of phase change and mode conversion in the pitch-catch method or additional reflections in the pulse-echo and phased-array methods.

Acoustic emission SHM has been found very useful in monitoring the initiation and growth of cracks during fatigue and/or stress-corrosion cracking of metallic structures [5–7] as well as for identifying impact events and disbonds/delamination growth in composites and bonded structures [8, 9]. AE sensors pick-up the minute acoustic waves (pops) that are generated in a structure as a crack is tearing its way through the structural material. The AE based SHM can exploit the repetitive nature of crack propagation events and has the potential of identifying damage well before it starts to affect the normal and safe operation of a structural system.

1.2. SHM sensors

Conventional ultrasonic transducers used in ultrasonic NDE and AE applications consist of a piezoelectric crystal connected to a wear plate and encapsulated into a protective casing. When excited by an electric pulse, the piezoelectric crystal resonates at its natural frequency which is typically into the hundreds of kHz and tens of MHz range. The crystal vibration is transmitted through the wear plate to the structural surface on which it sits and generates ultrasonic waves that travel through the structure. Conversely, elastic waves in the structure are picked up through the wear plate and produce resonant vibration of the crystal which is transduced by the piezoelectric effect into an electrical signal.

Although well established and widely available, the conventional ultrasonic transducers and AE sensors may not always be appropriate for permanent attachment in large numbers to an SHM structure due to their size and cost. Hence, a number of SHM-specific sensors have been developed that are smaller, less intrusive, and sometimes even cheaper than conventional ultrasonic transducers and AE sensors. Common examples of such SHM sensors are the piezoelectric wafer active sensor (PWAS) transducers [10] and the fiber Bragg grating (FBG) optical sensors [11]. The PWAS transducers serve as both transmitters (exciters) and receivers (sensors) of structural guided waves, whereas the FBG sensors can only act as receivers (Recent developments have also achieved the generation of guided waves with FBG sensors through the thermo-optical effect [13], but the resulting amplitudes are still order of magnitude below those achieve with piezoelectric transducers).

1.2.1. Piezoelectric wafer active sensors. Miniaturized acousto-ultrasonic transducers, such as PWAS attached directly to structural elements, have gained large popularity due to their low cost, simplicity, and versatility. PWAS transducers are small, lightweight, and relatively low-cost transducers based on the piezoelectric principle. The direct piezoelectric effect converts the stress applied to the sensor into electric charge. Similarly, the converse piezoelectric effect produces strain when a voltage is applied to the sensor.

With a single installation of PWAS transducers, one can apply a variety of structural-sensing damage-detection methods including propagating Lamb waves, standing Lamb waves (electromechanical impedance) and phased arrays. See figure 1.

1.2.2. FBG sensors. Fiber optics sensors have known extensive development for SHM applications [21]. Optical fibers consist of a very small inner core (which has a high reflection index caused by germanium doping) and an outer part of pure glass with a smaller reflection index. Total internal reflection takes place due to the large difference in the reflection indices. The FBG sensor (figure 2) is a permanent periodical perturbation (grating) in the index of refraction of the optical fiber core inscribed at selected locations using high-intensity UV light. This periodic perturbation with pitch acts as a wavelength filter with a narrowband reflection spectrum centered on the Bragg wavelength \( \lambda_B = \frac{2n_eff A}{\Lambda} \) (figure 2(b)). When mechanical strain \( \Delta \varepsilon \) and temperature change \( \Delta T \) are present, the Bragg wavelength shifts with [11]

\[
\Delta \lambda_B = \Delta \lambda_{BS} + \Delta \lambda_{BT} = \lambda_B (1 - \rho_a) \Delta \varepsilon + \lambda_B (a + \xi) \Delta T,
\]

where \( \xi \) is the thermo-optic coefficient and \( \rho_a \) is the effective strain-optic coefficient. If the temperature is constant, only the effect of strain is present. Thus, an FBG sensor bonded to a structural surface would respond to the structural strain by shifting its spectrum.

Fiber optics sensors offer several advantages over piezoelectric sensors for SHM applications: (a) immunity to electromagnetic interference (EMI); (b) corrosion resistance; (c) the promise of direct embedment into the composite material along with the reinforcing fibers; (d) capability of working in wet and/or underwater environments, etc. In addition, FBG sensors offer the possibility of multiplexing several sensors of slightly different wavelength on the same optical fiber and interrogating them individually. The methods used for the demodulation and interpretation of the optical signal are very diverse and still evolving.

1.3. Interaction of SHM sensors and the ultrasonic guided waves traveling in the structure

Surface bonding or embedding into closed-up structural cavities are the two main ways of integrating the SHM sensors into a host structure. The instrumentation of piezoelectric sensors such as the PWAS transducers is simple and straightforward because they directly convert strain into electrical voltage and vice-versa. The instrumentation of FBG optical sensors is more elaborate because it requires converting optical filtering changes into actual strain readings that initially generated those optical changes (stretching or compression of the FBG sensors shifts its optical wavelength and its filtering characteristic). One common way of using the FBG sensor for strain measurements is to track the spectral shift \( \Delta \lambda_B \) of the reflected signal and convert it into strain change \( \Delta \varepsilon \). However, this type of demodulation is only effective for
sizable strain values (say, several με) and is not effective for the very small strains encountered in ultrasonic wave propagation which are several order of magnitude smaller (με−0.001 0.100). Most commercial FBG sensing systems are built for relatively large strains and low frequencies and are not effective in detecting the low amplitude elastic waves of relatively high ultrasonic frequencies encountered in active ultrasonics and AE applications [25].

Wild et al [22] reviewed acoustic and ultrasonic optical sensors including FBG. Work on FBG for ultrasonic measurements began in 1996 [23] for sensing ultrasonic fields for medical applications. The demodulation method used for the detection of such small strains is based on up and down excursions from the midpoint of spectral slope. This so-called FWHM (full-width half-maximum) intensity modulation method [11] uses a narrow-band tunable laser source (TLS) precisely positioned on the FWHM point of the spectrum and several optical components to direct the reflected optical signal to a low-noise photo detector where it is converted into an electrical signal that can be fed into an oscilloscope for display and digitization. Recent developments in high-resolution TLSs and the FWHM principle have opened the possibility of using FBG sensors for active SHM and AE applications [1, 16–18]. Fomitchov and Krishnaswamy [24] studied the use of a FBG for the detection of ultrasonic waves in liquids and solid structures. Their system uses a tunable laser tuned to the FWHM point of the FBG, and a photodetector to measure the reflected intensity. They report sensitivity over a broad frequency range from 10 kHz to 5 MHz. Norman et al [3] developed an automated intensity-based system using the same method as the one Fomitchov used. Their system was capable of scanning of FBG arrays across several fibers using a fiber optical switch. Their system exhibited good strain sensitivity (<1 microstrain) and frequency response. Research has shown that the experimental investigation of fatigue crack in stainless with a FBG ultrasonic sensor determine the location of crack tip more precisely than piezoelectric sensors [20]. Significant advances have been made such that optical FBG sensors are now able to detect guided wave of nano-strain amplitude up into the MHz range [14].

It is apparent that the guided-wave particle motion contains both in-plane and out-of-plane components;
however, the sensors used to pick up the wave motion are selective in how they couple with the structure. On the one hand, conventional ultrasonic and AE sensors are sensitive only to the out-of-plane motion of the structural surface. This out-of-plane motion is picked up by resonant piezoelectric crystal through the wear plate that is in contact with the structural surface. On the other hand, PWAS transducers and FBG sensors bonded to the structural surface are sensitive to the in-plane surface strain of the structure transmitted through the adhesive layer. The surface mounted PWAS and FBG sensors stretch and compress as the structural surface stretches and compresses. The comparison of SHM sensors is shown in Table 1.

<table>
<thead>
<tr>
<th>Sensor type</th>
<th>Physical principle</th>
<th>What it detects</th>
<th>Azimuthal directionality</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional ultrasonic transducers and AE sensor</td>
<td>Piezoelectric resonator</td>
<td>Out-of-plane motion</td>
<td>Omnidirectional</td>
</tr>
<tr>
<td>PWAS</td>
<td>Piezoelectric (nonresonant)</td>
<td>In-plane strain</td>
<td>Omnidirectional</td>
</tr>
<tr>
<td>FBG</td>
<td>Optical reflection</td>
<td>In-plane strain</td>
<td>Longitudinal</td>
</tr>
</tbody>
</table>

1.4. The piezo-optical ring sensor concept

The general concept of the piezo-optical ring sensor is part of a wider invention disclosure for which an US patent application has been filed [15]. In the present article, we will discuss the scientific aspects of this invention and the modeling, design, fabrication, and experimental tests that have accompanied its development.

The aim of the piezo-optical ring sensor concept is to develop a novel acousto-ultrasonic sensor that uses optical FBG sensing principles to detect low-amplitude ultrasonic guided waves and acoustic emission AE events. The improvements that the piezo-optical ring sensor has over the surface mounted FBG sensors are:

(a) omnidirectionality, i.e., capability to sense guided waves coming from all directions,
(b) sensitivity to vertical wave motion, similar to the conventional AE sensors,
(c) tuneability to certain frequencies in which the AE signal is expected to be predominant.

An optical FBG sensor is bonded across the ring diameter; this FBG sensor will be stretched and compressed as the ring performs its in-plane resonant vibration. Thus the concept is that the ring picks up vertical motion from the structure, then enters in resonant vibration, and this vibration stretches and compresses the FBG sensor. In this way, the structural motion is picked up, filtered, and amplified by the ring, and converted to a sensing signal by the FBG sensor. This concept offers a novel and unprecedented solution for acousto-ultrasonic measurements that is beyond state of the art. We dubbed our concept ‘piezo-optical ring sensor’ because it combines the FBG detection with the ring mechanical resonance enhancement. To design and develop the piezo-optical ring sensor, we use both analytical methods (2D) and numerical methods (FEM) to predict its behavior.

Subsequently, we produced blueprints, fabricated several prototypes, and subjected them to extensive experimental testing.

2. Analysis, design and manufacturing of the piezo-optical ring sensor

The analysis and design of the piezo-optical ring sensor took place in stages. In the first stage, we developed an initial design based on the resonance motion of a ring undergoing flexural vibration. Subsequently, we refined the initial design by adding practical features like flat surface to make contact with the monitored structure and elliptical inner shape to force the resonant vibration in a certain direction along which to apply the FBG optical fiber sensor. Eventually, we proceeded to manufacture several prototypes of the refined design, notably for 100 kHz and 300 kHz resonances.

2.1. Initial ring sensor concept

In the early stages of the piezo-optical ring sensor development, we studied the resonance properties of a generic isotropic ring of axisymmetric construction. We used both an analytical approach and a numerical approach. The analytical approach was based on the 2D analysis of ring vibration [19]; the numerical approach used a 3D finite element method (FEM) the commercially available ANSYS WB software package. Blevins [19] gives analytical formulae for calculating the frequencies and modes of a slender isotropic ring. The flexural frequency formula is

\[
 f_i = \frac{i (i^2 - 1)}{2\pi R^3 \sqrt{(i^2 + 1)}} \sqrt{\frac{EI}{m}},
\]

where: \(i\) is the mode number; \(R\) is the radius of the midline of the ring; \(E\) is the modulus of the ring; \(I\) is the moments of inertia about the midline of the ring; \(m\) is the mass per unit length; \(f_i\) is the natural frequency of the \(i\)th mode. The first mode is a rigid-body mode which is antisymmetric about the mid-diameter; the second mode is a symmetric mode; whereas the third mode has a three-lobe shape. It is apparent that the mode of interest to us is the second mode because this mode would produce the stretching of an FBG fiber.

2.2. Refined ring sensor concept

In previous section, we showed that a ring with a prescribed flexural resonance frequency can be designed by using the formula of equation (2) to estimate some initial dimensions

\[
 f_i = \frac{i (i^2 - 1)}{2\pi R^3 \sqrt{(i^2 + 1)}} \sqrt{\frac{EI}{m}},
\]
and then using a full 3D FEM analysis to converge on the final design that meets the prescribed frequency with a reasonable accuracy. In this section, we discuss the final step from the ring concept to an actual prototype piezo-optical ring sensor. Three more concerns had to be addressed to ensure a correct functionality of our concept.

The first concern was that we needed to break the perfect axis symmetry of the ring by changing from a circular to an elliptical inner hole. With an elliptical inner hole, the maximum amplitude of vibration will always happen along the major axis of the ellipse and it is along this major axis that the FBG fiber is to be placed in order to pick up the ring vibration.

The second concern was that we needed to consider how the ring sensor is to be mounted onto the structure. When a cylinder sits on a plane, the contact between the cylinder and the plane is just a line of infinitesimal width, which offers an unsatisfactory footprint for connecting the ring to the structural surface. In order to increase the footprint and offer a reasonable contact area for proper adhesion, we decided to flatten the bottom of the ring. The flat was placed parallel to the major axis of the inner ellipse (figure 3(a)). Then, in order to maintain symmetry, we also flattened by an equal amount the top of the ring.

The third concern was about how to mount the FBG into the ring such as to be in the direction of the ellipse major axis. In order to make this possible, we drilled a hole in the ring walls along the major axis of the ellipse. Then we considered inserting the FBG fiber inside this hole and bonding it to the walls with adhesive. The bonding of the FBG fiber would be done with adequate pre-stress such as the fiber will be always in tension during its operation.

These design ideas were tested in ANSYS WB and the optimization procedure was applied until the desired frequency was again achieved. Designs were optimized for 100, 200, and 300 kHz rings. We found that by using our conceptual approach and adjusting the dimensions, we could design an improved piezo-optical ring sensor of virtually any desired frequency. The corresponding vibrational mode shape of the improved ring with the FBG fiber inserted in the center is shown in figure 3(b). These results shown in figure 3 confirm that the predicted resonance is an in-plane mode and matches the desired frequency. By placing the FBG fiber inside the ring (in the direction of the ring deflection), we will be able to have axial displacements on the fiber.

2.3. Manufacturing of the ring sensor prototypes

Since the 100 kHz piezo-optical ring sensor had more manageable dimensions (8.0 mm outside diameter), we attempted its manufacture in the university machine shop in close cooperation with our well-qualified machinists. We also found a local machine shop vendor (Alpha Manuf.) that was able to machine for us 300 kHz FBG ring sensors. The 304 stainless steel material was used. The internal ellipse shape was manufactured using the EDM process (electric discharge machining).

3. Testing of the piezo-optical ring sensor prototypes

The piezo-optical ring sensor prototypes were tested to determine its resonance frequencies from the spectral response. Two test methods were used (a) the electro-mechanical impedance spectroscopy (EMIS); and (b) the mechanical frequency response function (FRF).

3.1. EMIS testing of the piezo-optical ring prototypes

The EMIS is a convenient method of testing the vibration spectrum of a structure through a single measurement performed with an impedance analyzer which is connected directly to a PWAS transducer bonded to the structure. The vibration spectrum of the structure is reflected directly in the spectrum of the real part of the impedance Re(Z) measured on the PWAS terminals. The mechanical resonances of the structure appear as peaks in the Re(Z) frequency spectrum. A full description of the EMIS method together with theoretical justification accompanied by analytical and finite element models confirmed by a large number of experiments can be found in [10] chapter 9.

Figure 3(c) shows the spectrum of the impedance real part Re(Z) as measured on the 100 kHz ring prototype. According to the ring design and analysis, we expected the first resonant frequency to be around 100 kHz. Figure 3(c) indicates that the first resonance occurs at ~114 kHz, while higher resonances appear beyond 250 kHz. The actual 114 kHz resonance represents a 14% deviation from the design frequency. We believe that this discrepancy is due to the actual prototype not meeting exactly the design tolerances, which is understandable since it was manufactured in the school machine shop. Nonetheless, the fact that we have resonance-free frequency bands of ~100 kHz on both sides of this 114 kHz resonance peak attests that the purpose of the exercise, i.e., the manufacture of fully workable resonant sensor, has been fully met.

3.2. Frequency response testing of the piezo-optical ring prototypes

The frequency response testing measures the mechanical resonances in a more conventional way than the EMIS testing. The method consists in measuring the FRF between an actuator and a sensor placed on the structure. When the structure goes through mechanical resonances, the response measured by the sensor becomes very large. The FRF is represented by frequency domain plotting of the sensor response suitable scaled by the actuator input. The peaks of the FRF spectrum represent the resonance frequencies of the structure.

In order to measure the mechanical FRF of the ring sensor prototypes, we bound an additional PWAS on the other side of the ring as shown in figure 4. The specimen is now instrumented with two PWAS transducers: one excites the specimen and the other senses its vibration response. This process takes place in the time domain. An HP 33120A signal
Figure 3. Final concept for the piezo-optical ring sensor: (a) blueprints of the 100 kHz prototype; (b) 100 kHz modeshapes with the FBG fiber sensor inserted in the center; (c) results from EMIS spectrum of the 100 kHz prototype showing the fundamental resonance at 114 kHz.

Figure 4. Experiment setup for frequency response testing of the piezo-optical ring sensor prototypes.
generator was used to apply a 5-Vpp chirp signal excitation in a predetermined frequency range. The chirp signal duration was one second. This chirp signal was applied to the excitation PWAS. The response picked up by the sensor PWAS was measured with a Tektronix TDS5034B digital oscilloscope.

To improve the signal to noise ratio, several chirp repetition were applied and the signal was averaged by the oscilloscope. We found that self-triggering of the HP 33120A function generator is needed to ensure a consistent starting phase; this was achieved by feeding back the output to the trigger port located in the back of the HP 33120A function generator.

The testing of the 100 kHz prototype was done with a chirp excitation spanning the 1 Hz–250 kHz frequency range. The results of this test are shown in figure 5. In figure 5(a), a schematic representation of the linear frequency-time variation of the chirp excitation is shown. Figure 5(b) shows the time-domain specimen response; it is apparent that a strong resonance occurs around ~456 ms, which corresponds to ~114 kHz in figure 5(a). Finally, figure 5(c) shows the fast Fourier transform (FFT) of the response signal. Again, a strong peak is observed at ~114 kHz. These results compare very well with results obtained from the EMIS testing as described in section 3.1. We conclude that, for our specimen, the resonances identified with the frequency response method and with the EMIS method are substantially the same. The frequency response test method used in this section is somehow more conventional whereas the EMIS test method used in section 3.1 is easier to implement.

3.3. Frequency response testing with FBG sensor attached to the ring

Previous experiments have confirmed that the ring sensors prototypes experience strong and clear resonances around the design points, i.e., ~114 kHz for the 100 kHz prototype and ~277 kHz for the 300 kHz prototype. However, the mode-shapes of these resonances could not be measured because of the tiny size of the specimen. We believed that these resonances are, as designed, breathing oscillations of the rings that would produce extension and contraction of the rings inner diameters, but this hypothesis had to be validated by experiments. In order to do this, we decided to use an FBG sensor bonded along the ring major axis. The FBG was 10 mm long with more than 90% reflectivity supplied by from AtGrating Technologies (www.atgrating.com/en/productview.asp?id=63). It is made from acrylate fiber (SMF-28e) with acrylate recoating. FBG sensor is located at the customized position (1-meter from one FC/APC connector, another 1-meter as pigtail). The FBG is apodized with a center wavelength at 1550 nm.

Since the FBG at our disposal had a length of 10 mm it seemed appropriate to bond it to the 100 kHz ring prototype which had an outside diameter of 8 mm. The resulting specimen was instrumented with the FBG optical sensor, where the PWAS on top of the ring was used as exciter and the FBG sensor was bonded across the major diameter of the ellipse. The measurement equipment for the FBG optical sensor consisted of a LUNA Phoenix 1400 TLS, an optical circulator (AFW Technologies Pty, #CIR-3-15-L-1-2), a 50/50 optical splitter (AFW Technologies Pty, #FOSC-1-15-50-C-1-S-2), and a PDA10CF photodetector. The output signal from the photodetector was sent to a Tektronix TDS5034B digital oscilloscope that also served as signal digitizer.

The frequency response test procedure presented in section 3.2 was repeated with slightly modified parameters: The chirp signal spanned 50–150 kHz in 100 milliseconds. The time-domain response and its amplitude spectrum are shown in figure 6. In addition to a strong resonance peak seen at 102.1 kHz, some additional response is seen up to ~120 kHz. This is in slightly different from the results on the stainless steel 100 kHz ring presented in section 3.2, which saw the resonance peak at ~114 kHz. One possible
explanation for this difference might be in the fact that actual material properties of stainless steel and aluminum alloy as well as the actual manufacturing dimensions and shape are somehow different from the values considered in the design analysis. For the present, we are satisfied that the \(~100\mathrm{kHz}\) resonance of the ring is, as expected, of a “breathing” nature, i.e., it produces a periodic stretching of the FBG sensor.

4. Testing the piezo-optical ring sensor on an aluminum plate

The EMIS and frequency response testing of the ring sensor prototypes has shown good agreement between the predicted resonance frequencies and the experimental measurements. At this stage, we can say that the concept has been proven for the ring sensor prototypes, and move on to the next set of experiments, specifically testing the ability of the piezo-optical ring sensor to pick up the guided waves traveling in a plate better than an FBG bonded directly to a plate surface. Two sets of tests were considered: (a) sensing of piezo-generated Lamb waves in a pitch-catch configuration, i.e., active SHM testing, and (b) sensing of simulated AE waves generated with a pencil lead break (PLB), i.e., passive SHM testing. PWAS and FBG sensors were bonded directly to the plate collocated with the piezo-optical ring sensor as a basis for comparison. A large number of experiments were conducted. Some of the salient results are presented next.

4.1. Experimental setup for testing the piezo-optical ring sensor on an aluminum plate

The piezo-optical ring sensor was tested on a \(1200\text{ mm} \times 900\text{ mm} \times 1.2\text{ mm}\) 2024-T3 aluminum plate; the test plate was instrumented with the following sensors and transducers (see figure 7 for details):

- One PWAS was bonded to the top of the ring.
- One FBG was bonded to the side of the ring at its thickest region.
- One PWAS receiver was bonded to the plate in the immediate proximity of the ring.
- One FBG optical sensor bonded to the plate in the immediate proximity of the ring. The FBG sensor’s longitudinal direction was parallel to the axis of the ring’s elliptical hole.
- Two PWAS transmitters were placed 150 mm away from the cluster of receivers.
4.2. Pitch-catch testing on the aluminum plate

Pitch-catch experiments were performed using, in turn, the longitudinal exciter PWAS and the transverse exciter PWAS. Three-count Hanning windowed tone bursts over a 30–150 kHz frequency range was swept in 3 kHz steps and the received waveforms were sensed by (a) the PWAS on the plate, (b) the PWAS on the 100 kHz ring sensor, (c) the FBG on the plate, and (d) the FBG on the ring sensor. The tuning curves were assessed for transmission of the A0 mode from the longitudinal transmitter PWAS to both receiver PWAS and FBG sensors. The tuning was performed by measuring the amplitude of the received A0 wave packet for various excitation frequencies (see [10], chapter 8 for details on PWAS tuning principles).

The tuning results for the PWAS and FBG bonded to the plate and ring sensor are shown in figures 8(a), (b). For the PWAS and FBG on the plate, it is apparent that the A0 mode experiences a maximum tuning at low kHz frequencies (~40 and ~70 kHz) and subsequently decays. This behavior is recorded by both the receiver PWAS bonded to the plate (figure 8(a)) and by the FBG optical sensor bonded to the plate (figure 8(b)); the small discrepancy observed between maximum tuning frequency is due to the effect of the receiver PWAS size on the tuning curve.

The behavior of the signals measured on the 100 kHz ring sensor (figures 8(c), (d)) are substantially different, showing peaks around the ring sensor’s resonance frequency (~114 kHz from EMIS and frequency response testing in sections 2.2 and 3.2).

The PWAS signal of figure 8(c) has a sharper, clearly defined peak, whereas the FBG signal of figure 8(d) has a flatter peak spread over a wider frequency range. The explanation of these differences has still to be found through further, more detailed experiments.

Comparing the tuning curve amplitudes, at first glance it seems surprising that the response of the FBG and PWAS on the ring sensor has a lower amplitude than their respective counterparts on the plate. However, the mechanism of sensing is different; the FBG and PWAS on the plate detect surface strain, whereas the FBG and PWAS on the ring detect vertical motion. Additionally, the tone burst excitation has a spread about its center frequency, and only the frequency content overlapping with the resonance frequency of the ring sensor is sensed and amplified. This also applies to the observation that the tuning curve has a wider response than the FRF results which is characterized by a sharp peak, as the excitation itself has a wider frequency band.

4.3. Mode selectivity properties of the piezo-optical ring sensor

The capacity of the piezo-optical ring sensor to respond to A0, but not S0 waves and was also tested. Figure 9 shows the signals picked up by two co-located FBG sensors, one bonded directly to the plate (figure 9(a)) and the other bonded to the 100 kHz ring sensor (figure 9(b)). Both signals show the A0 packet, but the signal from the plate-mounted FBG in figure 9(a) also has a strong S0 packet which is almost missing from the ring sensor’s FBG signal in figure 9(b).

The explanation for this difference resides in the fact that the FBG bonded to the plate picks up the in-plane strain in the plate, whereas the piezo-optical ring sensor picks up the out-of-plane motion of the plate. Both the A0 and the S0 guided wave modes have significant in-plane strain components, hence both A0 and S0 packets show in figure 9(a). But only the A0 mode (which resembles a flexural wave) has significant out-of-plane motion whereas the S0 mode (which resembles an axial wave) has very small out-of-plane motion. Since the S0 mode has very small out-of-plane motion, it contribution to the signal picked up by the piezo-optical ring sensor is also very small.

4.4. Omnidirectional sensitivity of the piezo-optical ring sensor

Another important property that was verified through the wave propagation experiments performed on the aluminum plate was the omnidirectional sensitivity of the ring sensor. Recall that an FBG sensor engraved into an optical fiber is nominally sensitive only to strain along the longitudinal axis of the fiber. If waves travel along a plate at an angle to the fiber, the FBG readings are affected by a trigonometric projection; FBG readings from waves traveling transverse to the fiber are very small and only occur due to a secondary Poisson effect.

This behavior was tested by measuring the response of the FBG sensors mounted to the ring sensor and the plate to guided waves transmitter longitudinal to the fiber axis and transverse to the fiber axis. This was achieved by applying a 99 kHz excitation to the longitudinal and transverse transmitter PWAS from figure 7. The resulting waveforms are shown in figure 10.

For the plate-mounted FBG, the waveform captured from longitudinal excitation (figure 10(a)) showed much higher amplitude than the waveform from transverse excitation (figure 10(b)). This is as expected, as the FBG senses strain predominantly along the axis of the fiber. In contrast to the plate-mounted FBG, the piezo-optical ring sensor has
shown much less directional dependence, as illustrated in figures 10(c), (d). The FBG bonded to the ring sensor measured waveform signals that were only slightly different in magnitude. The fact that its directionality is slightly elliptical, i.e., its sensitivity decreases in the transverse direction, must be further investigated in subsequent studies.

Figure 8. Tuning curves for A0 wave packet over the 30–150 kHz range: (a) measurement with the PWAS bonded to the plate; (b) measurement with the FBG optical sensor bonded to the plate; (c) measurement with the PWAS bonded to the ring sensor; (d) measurement with the FBG optical sensor bonded to the ring sensor.

Figure 9. Comparison of FBG response to 99 kHz multimode guided waves: (a) FBG glued to the plate surface receives both S0 and A0 waves; (b) FBG mounted on the ring sensor is only sensitive to A0 waves.

4.5. Simulated acoustic emission measurements on the aluminum plate

A series of simulated acoustic emission (AE) tests were performed on the aluminum plate. The AE events were simulated with a 2H-hardness 0.3 mm PLB. The PLBs were
applied at 100 mm with a longitudinal transmission path from the PWAS on the plate and the PWAS on the ring sensor. The AE waveforms received by the PWAS bonded to the plate and the PWAS bonded to the ring sensor are shown in figure 11. Also shown in figure 11 are the frequency contents of these signals as obtained by FFT. It is apparent from figures 11(a), (c) that a clear, high-amplitude signal was received by both the PWAS on the plate and the ring sensor. However, it apparent that the waveforms are clearly different between figures 11(a), (c), i.e. figure 11(c) shows the PWAS bonded to the ring sensor detecting a much tighter AE wave packet than the waveform in figure 11(a). That fact is greatly advantageous in processing the AE waveform. These differences were further clarified by the examination of the frequency domain spectra presented in figure 11(b), which shows a wider bandwidth that the spectra in figure 11(d). In addition, the spectra in figure 11(d) shows clear high-frequency peaks which were not observed in figure 11(b). The explanation for the differences lies again in the resonant characteristics of the piezo-optical ring sensor which filtered out quite successfully the low-frequency excitation inadvertantly introduced by the PLB event.

It should be noted that if the piezo-optical ring can be designed to pick up AE events, then it will offer great advantages in terms of isolation from other noise sources and dynamic range improvement. However, further comparative exploration of the AE sensitivity needs to be done to draw a well-documented conclusion.

5. Summary, conclusions, and suggestions for further work

This paper has discussed a novel method and sensor for the detection of ultrasonic waves for enhancing the guide-wave SHM processes. The method, providing significant detection improvements, consists of developing a sensor that can detect the ultrasonic out of plane motion with preference for a certain predetermined frequency (e.g., 100, 200, 300 kHz). Both active SHM (pitch-catch) and passive SHM (simulated acoustic emission, AE, events) were considered. The new
sensor concept described in this paper uses piezoelectric PWAS and optical FBG sensing principles combined with mechanical resonance amplification concepts. The resonant principles offer enhanced sensitivity at the design bandwidth while filtering out unwanted noise and low-frequency vibration that would otherwise affect the dynamic range of the FBG sensor. We chose a ring sensor shape with an elliptical center hole to be able to predict in-plane displacement.

The paper has discussed the various developmental stages, from the basic concept of a resonant ring to the actual FEM analysis, design, and manufacturing of 100 kHz and 300 kHz prototypes. The main issues covered in the paper are: (a) study the mode shapes of the sensors under different resonance frequencies in order to understand the behavior of the ring in a frequency band of interest; comparison of analytical results and shapes with FEM predictions, (b) choice of the final piezo-optical ring sensor shape and (c) testing of the piezo-optical ring sensor prototypes both in isolation and as applied to an aluminum plate.

We found a very good agreement between experiments and the predicted resonance frequencies. In sum, experiments proved that the concept is working including the features of omnidirectionality, mode selectivity, and tuneability, and offers promise for further development. However, considerable further work is still needed to bring it to commercial use.

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References


Figure 11. AE waveform received by the PWAS bonded to the plate. Longitudinal excitation (a) time domain, (b) frequency domain. Transverse excitation: (c) time domain; (d) frequency domain. The simulated AE source was a pencil lead break (PLB) applied at 100 mm from the sensor, one time along the FBG fiber, the other time transverse to the fiber.


